

Modeling evapotranspiration and surface energy budgets across a watershed

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Abstract. Transport of mass and energy between and within soils, canopies, and the atmosphere is an area of increasing interest in hydrology and meteorology. On arid and semiarid rangelands, evapotranspiration (ET) can account for over 90% of the precipitation, making accurate knowledge of the surface energy balance particularly critical. Recent advances in measurement and modeling have made the accurate estimate of ET and the entire surface energy balance possible. The Simultaneous Heat and Water (SHAW) model, a detailed physical process model capable of simulating the effects of a multispecies plant canopy on heat and water transfer, was applied to 2 years of data collected for three vegetation types (low sagebrush, mountain big sagebrush, and aspen) on a semiarid watershed. Timing and magnitude of ET from the three sites differed considerably. Measured and simulated ET for approximately 26 days of measurement in 1990 were 41 and 44 mm, respectively, for the low sagebrush, 74 and 69 mm for the mountain big sagebrush, and 85 and 89 mm for the aspen. Simulated and measured cumulative ET for up to 85 days of measurement at the three sites in 1993 differed by 3–5%. Simulated diurnal variation in each of the surface energy balance components compared well with measured values. Model results were used to estimate total ET from the watershed as a basis for a complete water budget of the watershed.

Introduction

Transport of mass and energy between and within soils, canopies, and the atmosphere is an area of increasing interest in hydrology and meteorology. Recent advances in measurement and modeling have made it possible to accurately estimate evapotranspiration (ET) and the entire surface energy balance. On arid and semiarid rangelands, ET can account for over 90% of the precipitation, making accurate knowledge of the surface energy balance particularly critical. However, soils and vegetation vary considerably on rangeland, complicating efforts to estimate the ET portion of the water budget on even small rangeland watersheds.

Many studies have been reported which measured the energy balance over croplands and forests [Kim *et al.*, 1989; Lafleur, 1992; Malek, 1993; Massman and Ham, 1994; McGinn and King, 1990], but relatively few have focused on rangelands [Massman, 1992; Stannard *et al.*, 1994]. Models for simulating the energy balance for vegetative surfaces are available [Watts and Hanks, 1978; Stockle and Campbell, 1989; Luo *et al.*, 1992], including some developed for sparse vegetative cover [Nichols, 1992; Van Bavel *et al.*, 1984; Lascano *et al.*, 1987; Horton, 1989]. Flerchinger and Pierson [1991] presented additions made to the Simultaneous Heat and Water (SHAW) model to simulate heat and water movement through a vegetative canopy. The SHAW model is a detailed process model which simulates heat and water movement through a plant-snow-residue-soil system originally developed by Flerchinger and Saxton [1989] to simulate coupled heat and water movement related to soil freezing and thawing. The SHAW model differs from most models

which simulate the surface energy balance in that transpiration is linked mechanistically to soil water by computing flow through plant roots and leaves within the soil-plant-atmosphere continuum while satisfying a leaf energy balance. The model has the capability to simulate heat and water transfer through a multispecies canopy and directly computes soil evaporation separately from transpiration. The plant canopy is divided into layers, and evaporation from the soil is computed directly by solving heat and water transfer through each layer within the canopy.

Numerous studies have been conducted to test various aspects of the SHAW model, including variability of soil temperature and moisture due to vegetation effects [Flerchinger and Pierson, 1991, 1996], snowmelt and soil freezing [Flerchinger and Saxton, 1989; Flerchinger and Hanson, 1989; Flerchinger *et al.*, 1994a; Hayhoe, 1994], and evaporation. However, the ability of the model to simulate ET and the entire surface energy balance has never been adequately tested. The primary purpose of this paper was to test the ability of the model to simulate the temporal surface energy balance of three types of vegetation across a small semiarid watershed. A secondary objective was to obtain an estimate of total ET for the watershed to be used in computing a water balance for the watershed.

The SHAW Model

The physical system described by the SHAW model as presented by Flerchinger and Pierson [1991] consists of a vertical, one-dimensional profile extending from the vegetation canopy, snow, residue, or soil surface to a specified depth within the soil (Figure 1). The system is represented by integrating detailed physics of a plant canopy, snow, residue, and soil into one simultaneous solution. Interrelated heat, water, and solute

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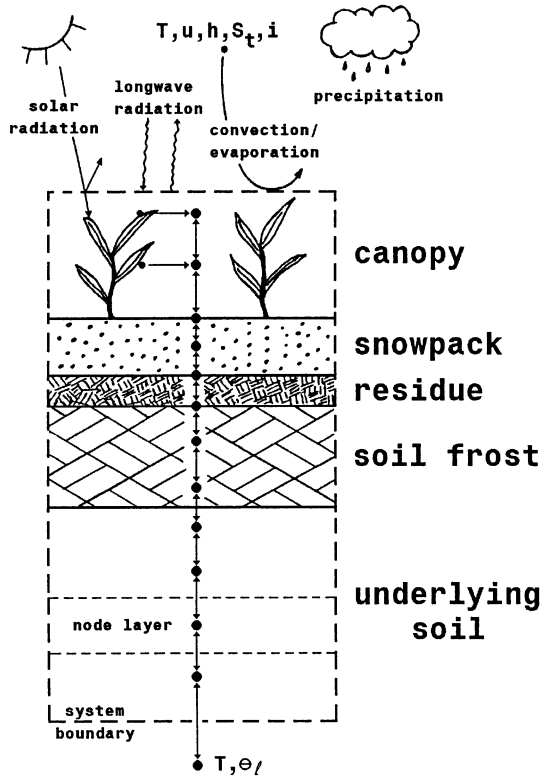


Figure 1. Physical system described by the Simultaneous Heat and Water (SHAW) model. (T is temperature, u is wind speed, h is relative humidity, S_t is solar radiation, i is precipitation, and θ_l is water content.)

fluxes are computed throughout the system and include the effects of soil freezing and thawing. Daily or hourly predictions include evaporation, soil frost depth, snow depth, runoff, and soil profiles of temperature, water, ice, and solutes.

Daily or hourly weather conditions above the upper boundary and soil conditions at the lower boundary define heat and water fluxes into the system. A layered system is established through the vegetation canopy, snow, residue, and soil, with each layer represented by a node. After computing flux at the upper boundary, the interrelated heat, liquid water, and vapor fluxes between layers are determined. Heat, water, and solute flux for the system are computed simultaneously using implicit finite difference equations and solved iteratively using a Newton-Raphson procedure [Campbell, 1985]. The model is capable of simulating several different plant species simultaneously, including standing dead plant material (assuming that the different plant species are sufficiently intermixed so that they are competing for water and energy in a common profile). Amount of dry matter, size, and leaf area index of each plant species over the year is defined by the user.

Weather data including air temperature, wind speed, relative humidity, and solar radiation control the surface energy balance and define the upper boundary conditions for the system simulated by the SHAW model. The surface energy balance may be written as

$$\mathbf{R}_n + \mathbf{H} + L_v \mathbf{E} + \mathbf{G} = 0 \quad (1)$$

where \mathbf{R}_n is net radiation (watts per square meter), \mathbf{H} is sensible heat flux (watts per square meter), $L_v \mathbf{E}$ is latent heat flux (watts per square meter), \mathbf{G} is soil or ground heat flux (watts

per square meter), L_v is latent heat of evaporation (joules per kilogram), and \mathbf{E} is total ET from the soil and plant canopy (kilograms per square meter per second), where all fluxes are positive toward the surface.

Net Radiation

Solar and longwave radiation exchange between canopy layers, residue layers, and the soil surface is computed by considering direct and upward and downward diffuse radiation being transmitted, reflected, and absorbed. Transmissivity to direct radiation for each canopy layer is calculated from [Goudriaan, 1988]

$$\tau_{b,i} = \exp \left(- \sum_{j=1}^{NP} K_j L_{i,j} \right). \quad (2)$$

Here $\tau_{b,i}$ is the transmissivity to direct radiation for canopy layer i , $L_{i,j}$ and K_j are leaf area index and extinction coefficient for plant species j of the canopy layer, and NP is the number of plant species in the canopy layer. The extinction coefficient is dependent on the orientation of the plant leaves and the angle of incident radiation. The above equation may also be used as an approximate expression (error < 0.05 for $L_j < 2$) for diffuse transmissivity with K_j equal to 0.78 for randomly inclined leaves and 0.68 for vertically inclined leaves. Effective albedo of canopy layer i is calculated from a weighted average of albedo, leaf area, and extinction coefficient for each plant species within the layer by

$$\alpha_i = \frac{\sum_{j=1}^{NP} \alpha_j K_j L_{i,j}}{\sum_{j=1}^{NP} K_j L_{i,j}} \quad (3)$$

where α_j is the albedo of plant species j . Transmission to direct radiation within the residue layer is calculated from

$$\tau_b = (1 - F_r) \sin \beta \quad (4)$$

where F_r is the fraction of surface area covered by the residue layer and β is the angle which the Sun's rays make with the surface. Transmission to diffuse radiation within the residue layer is computed as

$$\tau_d = 0.667(1 - F_r). \quad (5)$$

Radiation reflected and scattered by each layer may be absorbed by adjacent canopy layers, residue layers, and the soil surface or lost to the atmosphere. Solar radiation balance computation for each canopy and residue layer is similar to that described by Norman [1979] and Bristow *et al.* [1986].

Transmission and absorption of longwave radiation are similar to solar radiation, with the exceptions that scattering of longwave radiation can be ignored and longwave emittance must be considered. A longwave radiation balance is calculated for the soil surface and for each residue and canopy layer based on the fluxes incident on and emitted by each side of the layer. For simplicity, longwave emittance by a canopy layer is calculated using a leaf temperature for all plant species equal to air temperature within the layer. Thus no longwave radiation exchange between plant species within a canopy layer is considered, and emitted longwave radiation is biased by the difference between canopy air temperature and leaf temperature. However, these simplifications are not significant for most situations.

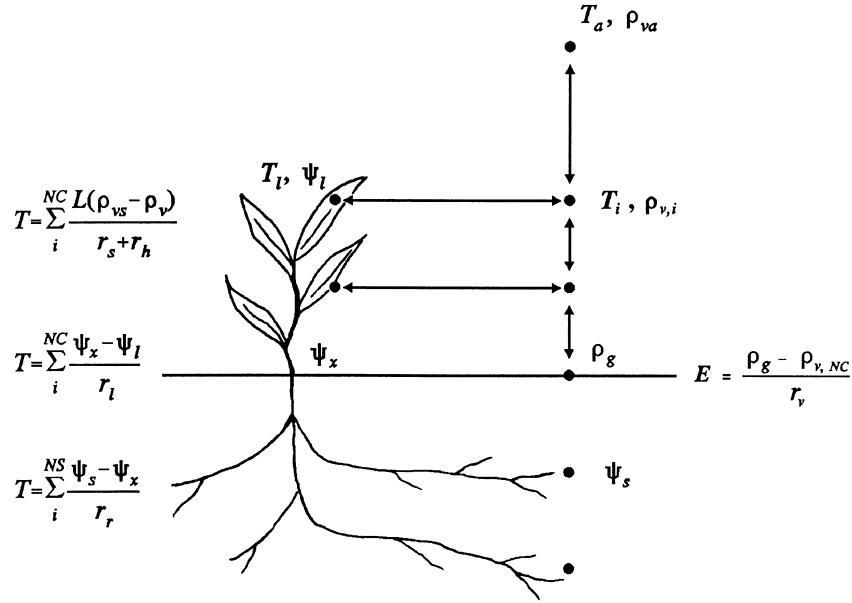


Figure 2. Physical representation of water flow through a plant in response to transpiration demands. (T_l is leaf temperature, ρ_g is vapor density at the ground surface, and r_v is resistance to vapor transfer within the canopy and equal to $1/k_e$; all other symbols are defined in the text.)

Sensible Heat Flux

Sensible and latent heat fluxes (watts per square meter) between the canopy-residue-soil surface and the atmosphere are affected by atmospheric turbulence and eddy exchange. Sensible heat flux is calculated from [Campbell, 1977]

$$H = \rho_a c_a [(T - T_a)/r_H] \quad (6)$$

where ρ_a , c_a , and T_a are the density (kilograms per cubic meter), specific heat (joules per kilogram per degrees Celsius), and temperature (degrees Celsius) of the air at reference height z , respectively, T is the temperature of the exchange surface, and r_H is the resistance to convective heat transfer (seconds per meter), computed from

$$r_H = (1/u^*k) \{ \ln [(z - d + z_H)/z_H] + \psi_H \} \quad (7)$$

where u^* is the friction velocity (meters per second), k is von Karman's constant, d is the zero plane displacement, z_H is the surface roughness parameter for the temperature profile, and ψ_H is the diabatic correction factor for heat, computed as a function of atmospheric stability.

Temperature of the exchange surface in the case of a plant canopy is the temperature of air within the first canopy layer, which is obtained by solving for heat transfer between canopy layers and from canopy elements (i.e., leaves and stems) within a canopy layer (Figure 2). Transfer between canopy layers depends on location within the canopy. Above the zero plane displacement d , transfer within the canopy is computed as

$$k_e = \rho_a c_a k u^* (z_s - d + z_H) / \zeta_s \quad (8)$$

and for heights less than d ,

$$k_e = \rho_a c_a k u^* z_H / \zeta_s \quad (9)$$

where z_s is height above the surface (meters) and ζ_s is a diabatic correction factor dependent on the Richardson number. Heat transfer and temperature within the canopy are

solved simultaneously with the energy balance of the entire profile by solving the implicit difference equations for each layer. Details are given by Flerchinger and Pierson [1991].

Latent Heat Flux

Transfer of water vapor (kilograms per square meter per second) from the exchange surface to the atmosphere is given by

$$E = (\rho_v - \rho_{va}) / r_v \quad (10)$$

where ρ_v is vapor density (kilograms per cubic meter) of the exchange surface and ρ_{va} is the vapor density at the reference height. The resistance to convective vapor transfer r_v is assumed to be equal to r_H , which is normally a close approximation when the wind speed is sufficient to enhance transfer above that of vapor diffusion rates. Vapor density at the exchange height is solved similarly to temperature at the exchange height in that transfer of water vapor is computed between canopy layers and from canopy elements as transpiration within a canopy layer.

Transpiration within a canopy layer is determined assuming a soil-plant-atmosphere continuum. Water flow is calculated assuming continuity in water potential throughout the plants as illustrated in Figure 2. Water flow is calculated from the water potential in the soil, through the roots, to the water potential in the plant xylem; from there to the leaf water potential in all canopy layers; and from stomatal cavities in the leaves through the stomates to the ambient air within the plant canopy. Water flow through the plant must meet transpiration demand and may be calculated at any point in the plant from

$$T = \sum_{m=1}^{NS} \frac{\psi_{s,m} - \psi_x}{r_{r,m}} = \sum_{i=1}^{NC} \frac{\psi_x - \psi_{l,i}}{r_{l,i}} = \sum_{i=1}^{NC} \frac{\rho_{vs,i} - \rho_{v,i}}{r_{s,i} + r_{h,i}} L_i \quad (11)$$

Here T is total transpiration rate (kilograms per square meter per second) for a given plant species; $\psi_{s,m}$, ψ_x , and $\psi_{l,i}$ are

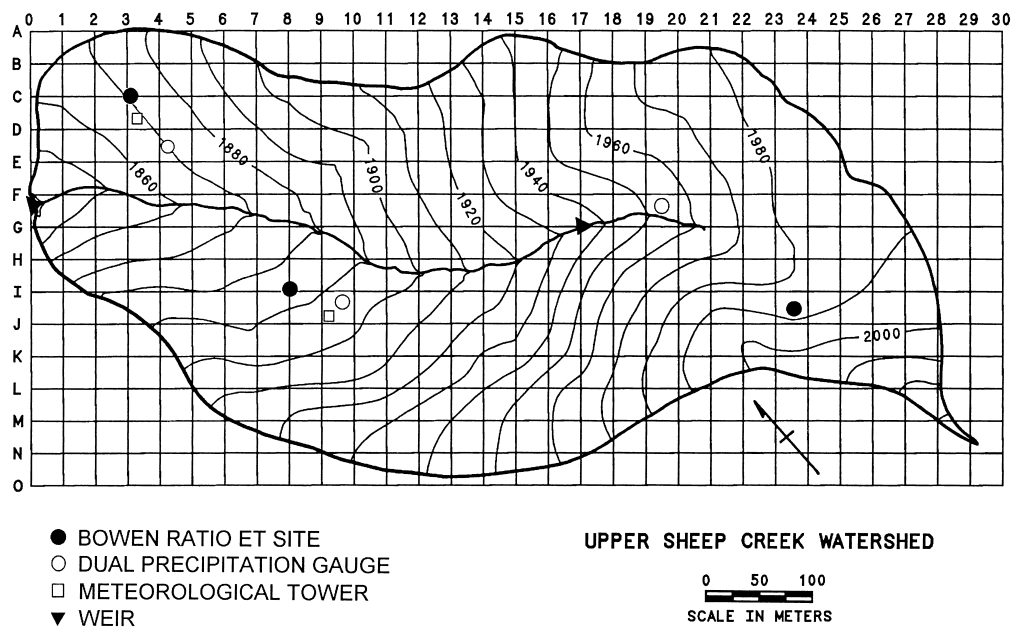


Figure 3. Topography and instrument locations within the Upper Sheep Creek Watershed. (Elevation is in meters. ET is evapotranspiration.)

water potential (meters) in layer m of the soil, in the plant xylem, and in the leaves of canopy layer i , respectively; $r_{r,m}$ and $r_{l,i}$ are the resistance to water flow (cubic meters per second per kilogram) through the roots of layer m and the leaves of layer i , respectively; L_i is leaf area index within canopy layer i for a given species; $\rho_{vs,i}$ is the vapor density within the stomatal cavities (assumed to be saturated vapor density); $\rho_{v,i}$ is the vapor density of the air within the canopy layer; $r_{s,i}$ is stomatal resistance per unit of leaf area index (seconds per meter); $r_{h,i}$ is resistance to convective transfer within layer i per unit leaf area index (seconds per meter); and NS and NC are the number of soil nodes and canopy nodes, respectively.

Within the plant, water flow is controlled mainly by changes in stomatal resistance. Neglecting other effects, a simplified equation relating stomatal resistance to leaf water potential is

$$r_s = r_{so} [1 + (\psi_l / \psi_c)^n] \quad (12)$$

where r_{so} is stomatal resistance with no water stress, ψ_c is a critical leaf water potential (at which stomatal resistance is twice its minimum value), and n is an empirical coefficient [Campbell, 1985].

Water uptake, transpiration, and leaf temperature are coupled through an energy balance of the leaf, which is calculated for each plant species within a canopy layer. Heat and water flux equations for canopy, snow, residue, and soil layer are written in implicit finite difference form and solved using an iterative Newton-Raphson technique [Campbell, 1985]. This involves writing a balance equation for each layer in terms of unknown end-of-time-step values within the layer and its neighboring layers. Partial derivatives of the flux equations with respect to the unknown end-of-time-step values are computed, forming a tridiagonal matrix from which the Newton-Raphson approximations for the unknown values are computed. Iterations are continued until successive approximations are within a prescribed tolerance. Additional details are given by Flerchinger and Pierson [1991].

Description of the Study Site

Upper Sheep Creek, located in the Reynolds Creek Experimental Watershed in southwestern Idaho, United States (43° 12'N, 116° 45'W), is an intermittent, first-order tributary of Reynolds Creek and has been described in detail by Flerchinger *et al.* [1992]. Elevation over the 26-ha watershed varies from 1840 to 2036 m. Figure 3 shows the watershed and locations on it referenced to a grid system. Average annual precipitation is approximately 508 mm, most of which occurs as snow. Snow cover on the watershed varies from shallow snow cover with large areas bare of snow for part of the winter to large drifts which typically remain into June.

Soils and vegetation at Upper Sheep Creek are strongly affected by wind, topography, and the effective precipitation patterns that result from drifting snow. Three distinct vegetation and soil types can be identified on the Upper Sheep Creek Watershed. These areas were referred to as low sagebrush, mountain big sagebrush, and aspen. The low sagebrush areas, located predominantly on the west facing slopes and ridge tops, are bare of snow for much of the winter as the snow melts off several times during the winter. The north facing slopes, with predominantly mountain big sagebrush, typically accumulate about a meter of snow during the winter. Aspen thickets have established themselves on the upper portions of the north facing slopes where large snow drifts are formed annually by prevailing southwesterly winter winds. The three units are delineated in Figure 4 and characterized below:

1. The low sagebrush/grasses (*Artemisia arbuscula*/*Poa secunda*) areas are sparsely covered (leaf area index less than 0.50) and have a considerable amount of bare ground. Soils are generally shallow (<30 cm) to basalt bedrock and have high rock content (>50%), relatively high clay content ($\approx 25\%$) argillic horizons, and thin (<10 cm) silt loam surface horizons.
2. The mountain big sagebrush/snowberry (*Artemisia tridentata vaseyana*/*Symphoricarpos spp.*) area is completely covered with taller sagebrush, snowberry, and grasses with leaf

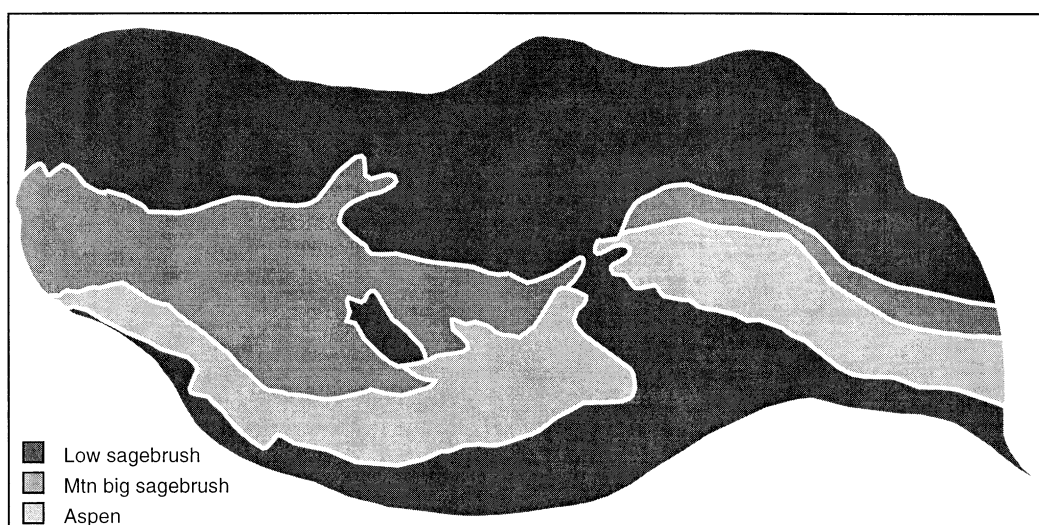


Figure 4. Delineation of the three vegetation types on the Upper Sheep Creek Watershed.

area index typically between 1.0 and 2.0. These soils are deeper to basalt bedrock (>100 cm) and have much lower rock contents within the upper meter, little argillic horizon development, and a relatively thick (50–100 cm) silt loam horizon.

3. The aspen/willow (*Populus tremuloides/Salix spp.*) unit is dominated by a thick stand of aspen and willow with peak leaf area index around 3. Soils are very deep to bedrock (>200 cm) and virtually rock free, have little argillic development, and are almost entirely composed of silt loam material.

Field Instrumentation and Data Collection

The instrumentation network in the Upper Sheep Creek basin was constructed in 1984 and consists of piezometers, snowmelt collectors, weirs, precipitation gauges, and meteorological instrumentation towers. Hourly meteorological information was collected at two sites on the watershed. Measurements on the northeast facing site near J9 (Figure 3) included air temperature, wind speed and direction, relative humidity, and incoming solar radiation, while those on the west facing slope near D4 included only air temperature and wind speed. Precipitation was measured at three sites in the watershed (Figure 3) using the dual gauge system, which consists of a shielded and an unshielded gauge [Hamon, 1973; Hanson, 1989].

Leaf area index measured using an inclined point frame was 0.42, 1.2, and 1.0 for the low sagebrush, the mountain big sagebrush, and the grass understory of the aspen site, respectively, at peak standing biomass. Leaf area of a single representative aspen measured at the peak of the growing season by destructive sampling was found to be 3.45. Transect measurements indicated aspen and willow covered approximately 58.9% of the area, yielding a tree leaf area index of 2.0 for the site. Leaf area index, plant height, and assumed rooting depth are given in Table 1. Soil hydraulic properties by depth were estimated from soil texture and density based on methodology presented by Saxton *et al.* [1986]. Soil water measurements used to initialize the model were collected approximately every 2 weeks at 11 sites across the watershed using a neutron probe.

A single Bowen ratio unit was rotated at weekly intervals among the three vegetation types when vegetation was actively

transpiring during 1990, and three separate units were set up continuously at the three sites during 1993. The units were located near C3 for the low sagebrush site, I8 for the mountain big sagebrush site, and I24 for the aspen site (Figure 3). The particular sites were selected to provide an optimum fetch over relatively uniform vegetation in all directions but most importantly in the direction of the dominant westerly winds.

The Bowen ratio [Bowen, 1926] and the energy balance equation are the basis for the Bowen ratio-energy balance method of determining ET using micrometeorological and soil heat flow measurements [Rosenberg *et al.*, 1983; Fritschen, 1966; Tanner, 1960]. Two types of systems were used to measure ET rates. A positive-head, ceramic-wick, aspirated psychrometer system similar to that described by Gay and Fritschen [1979], Gay and Greenberg [1985], and Gay [1988] was used during the 1990 growing season and at the aspen site during 1993. A cooled-mirror, dew-point hygrometer system was used at the low sagebrush and mountain sagebrush site during 1993. Comparison of these two units by Wight *et al.* [1993] gave essentially identical results.

Simulation of the Energy Balance

The Simultaneous Heat and Water (SHAW) model was used to simulate ET and the entire energy balance for the three vegetation types. Model simulations were compared with measured data collected while plants were actively transpiring. Results were used to compute total ET from the watershed.

Table 1. Vegetation Characteristics for Each Site

Site	Canopy Height, cm	Rooting Depth, cm	Leaf Area Index
Low sagebrush	15	40	0.4
Mountain big sagebrush	90	100	1.2
Aspen			
Trees	450	200	0–2.0
Grasses	30	100	0–1.0

Model Simulations

A separate model run was conducted for the low sagebrush, mountain big sagebrush, and aspen areas for each of 2 years of data. Simulations were conducted for the entire 1990 and 1993 water years (October 1 through September 30) to compute total ET for the watershed. Lack of soil water data in the fall of 1989 required using estimated soil water profiles to initialize the model for simulating the entire 1990 water year. Thus partial-year simulations were also conducted for 1990 starting with the first available soil water content measurements (day 142 for the low sagebrush and mountain big sagebrush sites and day 171 for the aspen site) to assess the effect of using estimated soil water content. Because soil temperature data were not available to specify the lower boundary, a 400-cm profile was simulated using 14 soil layers located at the surface, 5, 10, 15, 20, 30, 50, 70, 100, 125, 150, 200, 300, and 400 cm, respectively, for all sites. Soil temperature at 400 cm was assumed constant and equal to the annual average air temperature (6.9°C).

The model was run without prior calibration; however, previous experience with the model and values obtained from literature were required to parameterize the model. Parameters for root resistance r_r , total leaf resistance r_l , and unstressed stomatal resistance r_{so} for low sagebrush and mountain big sagebrush were set equal to $1.7 \times 10^6 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$, $6.7 \times 10^5 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$, and 100 s m^{-1} , respectively, based on data presented by Romo and Haferkamp [1989] and Miller [1988] and used by Flerchinger and Pierson [1991] in previous studies. Critical leaf potential ψ_c and the stomatal resistance exponent were taken as -300 m and 5 , respectively, based on calibration results for big sagebrush (*Artemisia tridentata wyomingensis*) conducted by Flerchinger and Pierson [1996] on a site within 11 km of the watershed. Total plant resistance for fescue is $1.15 \times 10^5 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$ (Burch [1979] as cited by Abdul-Jabbar et al. [1984]). Root resistance and total leaf resistance for grasses at the aspen site were therefore set to $0.77 \times 10^5 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$ and $0.38 \times 10^5 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$, respectively. (Campbell [1985] indicated that roughly 1/3 of the resistance to water flow within plants is encountered within the leaves.) Root and leaf resistances were not available for aspen and were set equal to $3.3 \times 10^5 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$ and $1.7 \times 10^5 \text{ m}^3 \text{ s}^{-1} \text{ kg}^{-1}$, respectively, which gives a total plant resistance roughly midrange of the values reported by Abdul-Jabbar et al. [1984] for other plants. Albedo was set to 0.15 for the sagebrush [Dirnhirn and Belt, 1971] and 0.25 for aspen leaves, which is typical for green leafy foliage. Zero plane displacement d and surface momentum and thermal roughness parameters, z_m and z_H , were calculated based on height of the canopy ($d = 0.77h$, $z_m = 0.13h$, and $z_H = 0.2z_m$ [Campbell, 1977]). Growth curves for grass and leaves for the aspen site were based on field notes. The aspen started to leaf out at approximately day 170 for both 1990 and 1993 and were fully leafed by day 200. Experience with the model suggests that leaf area index of a layer should not greatly exceed 0.75 for numerical convergence and efficiency. Thus a single canopy layer was used to simulate the low sagebrush site, two layers were used for the mountain big sagebrush, and up to four layers were used for the aspen site.

Model Sensitivity

Sensitivity of model results to total plant resistance (leaf plus root resistance) and initial soil water content was investigated. Although values of total plant resistance are given for a variety

of plants by Abdul-Jabbar et al. [1984] and have been included in the user interface for the SHAW model, these values can vary by orders of magnitude between plants and many researchers are not familiar with this parameter. Additionally, lack of measured initial soil water conditions for the fall of 1989 and spatial variability of soil water within the vegetation types necessitated a sensitivity analysis for initial soil water content.

To examine model sensitivity to total plant resistance, runs were conducted for each site using plant resistances $\pm 50\%$ of their selected values. Changing resistance values for the low sagebrush site had essentially no effect on total ET for water year 1990. This site is very dry, and the limiting factor for ET at this site is availability of water rather than plant characteristics. Decreasing resistance by 50% at the other two sites increased total ET for the year by approximately 6%. Because water availability was less of a factor for transpiration rate at these two sites, plant resistance had a greater effect on total ET. However, on the basis of the sensitivity, it takes a large change in plant resistance to significantly change ET.

The deepest soil moisture tube located nearest the Bowen ratio unit for each vegetation site was used to initialize the model. These were located at D4, I8, and I23 for the low sagebrush, mountain big sagebrush, and aspen sites, respectively. Total water measured within the root zone of the mountain big sagebrush and aspen areas during the spring of 1990 and 1993 varied by $\pm 5\%$ within each area for a given year. (Only one soil moisture tube existed in the low sagebrush area.) Thus the model was run for each of the vegetation types with soil water content increased by 5% to examine the effect of the spatial variability in soil water content. The largest observed effect was for the full-year run on the mountain big sagebrush site, in which simulated ET increased from 569 to 575 mm. (This site has a greater opportunity to take advantage of stored soil water carried over from one year to another; the low sagebrush site has a very shallow rooting depth and cannot store much water, while the aspen site normally receives sufficient input from the melting snow drift to saturate the soil profile.) Thus the spatial variability in soil water present within the vegetation types would have very little effect on estimated ET.

The summer of 1989 was extremely dry, and data from measured soil water profiles at nearby locations on the Reynolds Creek Experimental Watershed indicate some of the driest conditions on record. On the basis of this knowledge, soil water content profiles were estimated based on the driest observed soil water contents on record for each site. A comparison of the run for the entire water year and that using the first available soil water measurements in the spring of 1990 is given in Table 2. Differences between the two runs for the periods of measured ET are very minimal, which confirms the estimated soil water contents and speaks well of the overwinter soil water budgeting within the model.

Model Results

Model simulations were compared with measured data for periods where data were available in 1990 and for the entire period of measurement at each site for 1993. Diurnal and daily energy fluxes compared quite well with measured data. Comparison of measured and simulated diurnal variation in surface energy flux at peak transpiration rate for the three sites during 1990 is given in Figures 5 through 7 for the partial-year simulation. The coefficient of efficiency (defined as the variation in measured values explained by the model and analogous to the

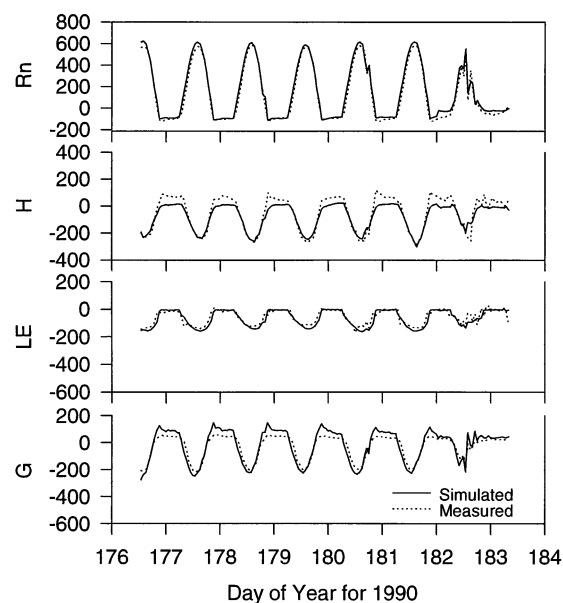
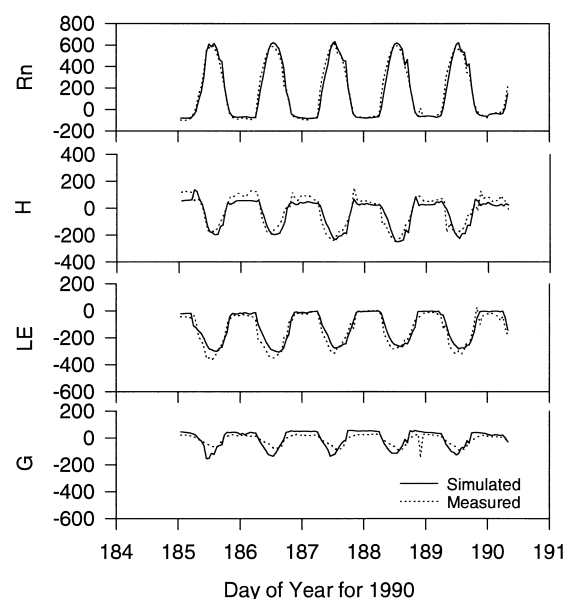
Table 2. Comparison of Simulated and Measured Evapotranspiration for 1990

Period (Day of Year)	Days	Full-Year Simulation, mm	Partial-Year Simulation, mm	Measured, mm	Error,* mm
<i>Low Sagebrush</i>					
135–140	6	7	...	9	–2
156–161	6	16	16	15	1
177–182	6	14	14	12	2
198–203	6	7	7	5	2
Total	24	44	...	41	3 (7%)
<i>Mountain Big Sagebrush</i>					
163–168	6	14	14	15	–1
185–189	5	20	20	24	–4
205–208	4	11	11	14	–3
233–238	6	14	14	13	1
261–266	6	8	10	8	2
Total	27	67	69	74	–5 (7%)
<i>Aspen</i>					
170–175	6	18	16	16	0
192–196	5	31	31	28	3
212–217	6	33	34	33	1
268–273	6	7	8	8	0
Total	23	89	89	85	4 (5%)

*Error in full-year simulation for low sagebrush and partial-year simulation for all others; positive error indicates overprediction by the model.

coefficient of determination [Kitanidis and Bras, 1980]) for simulated net radiation during 1990 ranged from 0.95 to 0.96. Coefficient of efficiency for hourly simulated latent heat ranged from 0.61 for the low sagebrush site to 0.78 for the aspen. A summary of total ET for the measurement period at each of the three sites is given in Table 2. Measured and simulated ET accumulated over the measurement periods were within 5–7%.

The portion of net radiation used for each of the components of the energy balance differed considerably between the

**Figure 5.** Simulated and measured diurnal variation in the surface energy balance (watts per square meter) at peak evapotranspiration for the low sagebrush. (Fluxes are positive toward the surface.)**Figure 6.** Simulated and measured diurnal variation in the surface energy balance (watts per square meter) at peak evapotranspiration for the mountain big sagebrush. (Fluxes are positive toward the surface.)

three sites and temporally at a given site. Table 3 gives the average net radiation available during selected periods for 1990 along with the percentage of net radiation used by other components of the energy balance. At peak transpiration rate, measured latent heat flux accounted for 49%, 79%, and 113% of the available net radiation for the low sagebrush, mountain big sagebrush, and aspen sites, respectively, compared to 51%, 71%, and 104% for the simulated values. The difference between the three sites is undoubtedly due to the difference in leaf area index between the three areas. The lowest ET rate

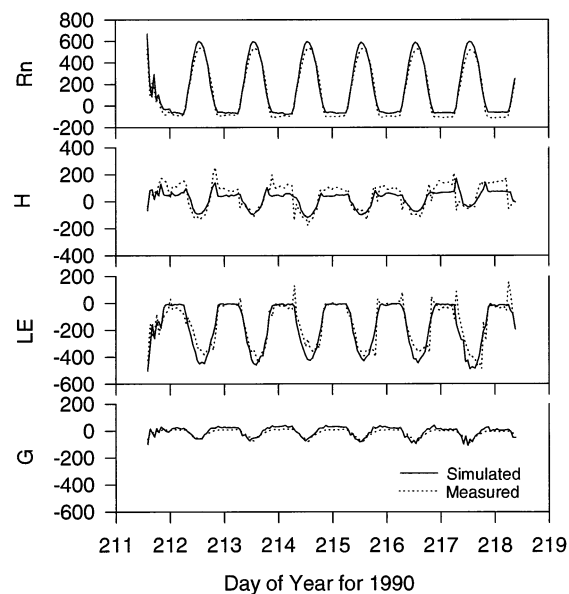
**Figure 7.** Simulated and measured diurnal variation in the surface energy balance (watts per square meter) at peak evapotranspiration for the aspen. (Fluxes are positive toward the surface.)

Table 3. Apportioning of Simulated and Measured Net Radiation Into Components of the Energy Balance for 1990

Period (Day of Year)	Measured				Simulated			
	R_n , W m^{-2}	H , %	L_vE , %	G , %	R_n , W m^{-2}	H , %	L_vE , %	G , %
<i>Low Sagebrush</i>								
156–161	139	31	49	20	149	36	51	14
198–203	120	65	17	18	133	66	25	8
<i>Mountain Big Sagebrush</i>								
185–189	179	13	79	8	182	23	71	6
261–266	61	33	60	7	67	28	72	1
<i>Aspen</i>								
170–175	168	35	49	17	155	22	61	17
212–217	142	–23	113	12	169	–8	104	4

from the aspen was measured prior to full foliage cover, at which time 49% of the measured net radiation went to latent heat, while simulated latent heat accounted for 61%. The percentage of net radiation consumed by latent heat varied least in the mountain big sagebrush area due to the ever-present foliage on the sagebrush and sufficient soil water storage. In comparison, latent heat transfer became a small component of the energy budget at the low sagebrush site late in the season as available soil water became limiting. The model simulated this shift in the energy budget for the low sagebrush site quite well (Table 3).

Simulated ET for 1993 for the low sagebrush, mountain big sagebrush, and aspen sites was 338, 505, and 456 mm, respectively, as shown in Figure 8 with the measured ET. Because of late-lying snow in the drift at the aspen site, the aspen site started actively transpiring much later in the season than the other two sites and actually had less cumulative ET than the mountain big sagebrush site, which had 60% less leaf area. Peak ET rate for the aspen site occurred around day 220 both years at a rate of approximately 6 mm d^{-1} compared to a peak ET of approximately 5 mm d^{-1} around day 180 for the moun-

tain big sagebrush and 3 mm d^{-1} around day 150 for the low sagebrush.

Watershed Evapotranspiration

Total ET for the watershed was computed using simulated ET at each of the sites based on a simple areal averaging as given in Table 4. This simple averaging is justified based on the fact that the vegetation types are rather distinct with little or no intermingling. Total simulated ET for the watershed was estimated at 450 mm for 1990 and 394 for 1993. A preliminary water balance of the watershed presented by *Flerchinger et al.* [1994b] using the estimated ET presented in Table 4 results in an error of 3 mm for 1990 and 51 mm for 1993. This corresponds to an error of 1 and 7% of the total precipitation for each year, respectively. Estimating total ET of the watershed using a simple areal average therefore does not result in significant errors in the overall water budget of the watershed.

Summary and Conclusions

The Simultaneous Heat and Water (SHAW) model is a detailed physical process model of a vertical, one-dimensional canopy-snow-residue-soil system. The system is represented by integrating detailed physics of heat and water transfer through a plant canopy, snow, residue, and soil into one simultaneous solution, which includes provision for soil freezing and thawing. The ability of the model to accurately simulate the surface energy balance for diverse sites was investigated by applying the model to 2 years of data from three sites within a semiarid watershed ranging from a sparsely covered, low sagebrush site to an aspen thicket with an understory of grass.

The model was applied to a 400-cm soil profile for the three sites. Diurnal variation in the energy balance was simulated with reasonable accuracy. Of the components of the surface energy balance, variation in net radiation was simulated with greatest accuracy, with over 95% of the variation in net radiation during 1990 being explained by the model. Simulated ET for approximately 25 days of measurement during 1990 was within 5–7% of measured values.

Differences in the surface energy balance between sites and temporal variation at each site were simulated well by the model. At peak transpiration the portion of net radiation attributed to latent heat varied from 49 to 113% between sites

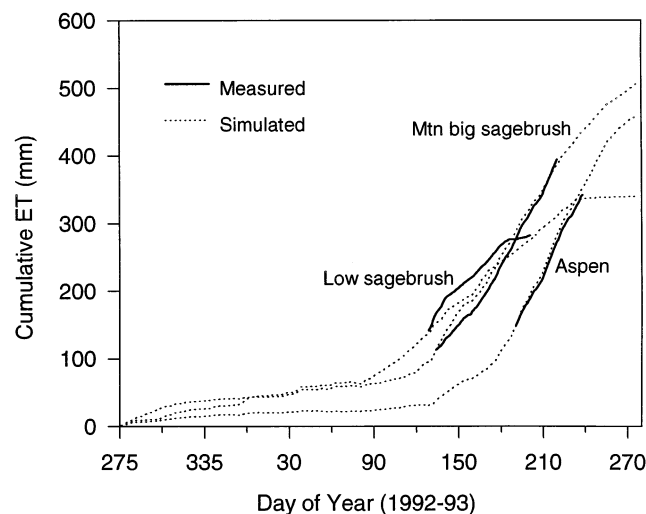


Figure 8. Simulated and measured cumulative evapotranspiration for the low sagebrush, mountain big sagebrush, and aspen for 1993 water year.

Table 4. Summary of Water Balance for Each Watershed Area

Water Year	Site	Area	Precipitation*	ET
1990	Low sagebrush	60.1%	406	376
	Mountain big sagebrush	21.0%	529	569
	Aspen	18.9%	733	570
	Area weighted average		494	450
1993	Low sagebrush	60.1%	576	338
	Mountain big sagebrush	21.0%	802	505
	Aspen	18.9%	889	456
	Area weighted average		682	394

Values are given in millimeters. ET is evapotranspiration.

*Precipitation for aspen area adjusted for drifting snow.

based on measurements. The portion of simulated net radiation attributed to latent heat varied from 51 to 104%, indicating the ability of the model to simulate differences in the surface energy balance across the watershed. The shift in the surface energy balance from latent heat loss to sensible heat loss as the soil dried and soil water became limiting was simulated with reasonable accuracy. A preliminary water budget of the watershed using total ET based on simulations from each vegetation type was within 1 and 7% for the 2 years. Thus results suggest that the model can simulate the variation in ET and the surface energy balance across a semiarid watershed having considerably diverse vegetation with reasonable accuracy.

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